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# A STUDY OF RAPID ENGINE RESPONSE SYSTEMS FOR AN ADVANCED HIGH SUBSONIC, LONG RANGE COMMERCIAL AIRCRAFT

by


J.H. Barber
G.W. Bennett
T.A. DeRosier

GENERAL ELECTRIC COMPANY




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Project Manager, Robert J. Antl, V/STOL & Noise Division
NASA Lewis Research Center
Cleveland, Ohio 44135

16. Abstract

A dynamic model representing the characteristics of an advanced technology study engine (1985 certification time period) was constructed and programmed on an analogue/digital computer. This model was then exercised to study and evaluate a large number of techniques, singly and in combination, to improve engine response. Several effective methods to reduce engine accelerating time are identified.

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## SUMMARY

A dynamic engine model representing the characteristics of an advanced technology study engine (1985 commercial certification time period) was constructed and programmed on an analogue/digital computer. This model was then exercised to study a large number of possible techniques, singly and in combination, to improve engine response time, while holding consistent and realistic engine constraints. The relative effectiveness of these techniques is presented.

Several effective methods to improve engine response time from flight idle (10% take-off thrust) to take-off thrust have been identified.

Improvements in engine response depend to a large extent on the degree of complexity (variable geometry) introduced. On the order of 25% to 35% reduction in acceleration time from flight idle (10% take-off thrust) to maximum thrust is shown to be achievable.

The impact on engine life, reliability, control complexity, etc., of any of the techniques exercised in this study, including those which utilize features that are already on the engine such as variable stators or bleed air extraction, must be assessed before any can be recommended.

It is not now known to what extent engine response time needs to be improved for different approach operational procedures. It is recommended that engine response requirements be established for representative aircraft by means of suitable analysis and simulator studies.

## INTRODUCTION

The two-segment glide slope landing approach, proposed as one of the noise abatement methods (Refs. 1 and 2), will require a thrust acceleration as the aircraft is transitioned from the initial glide slope to the final glide slope. There have been some studies which implied a requirement for improved transient thrust response at the transition from the initial glide slope to the less steep glide slope (Ref. 2). The wave-off or go-around during the landing procedure also requires fast-responding jet engines. These requirements for rapid thrust response have resulted in the efforts that are described in this report.

The techniques for improving the thrust response of the engine consisted of: (1) scheduling the variable geometry, (2) increasing the operating limits on some of the engine parameters, (3) water injection, and (4) compressor bleed. The study analyzed two general methods for improving the engine transient response. One method utilized the engine variables during acceleration to improve the engine transient response by increasing the unbalanced torque. The second method intentionally set up thrust attenuating or thrust losing techniques during the initial glide slope. Thus, to maintain the required thrust during approach, the engine was required to operate at higher rotor speeds to produce the needed thrust. This permitted the engine to be accelerated from higher base speeds and, therefore, resulted in a decrease in the acceleration time.

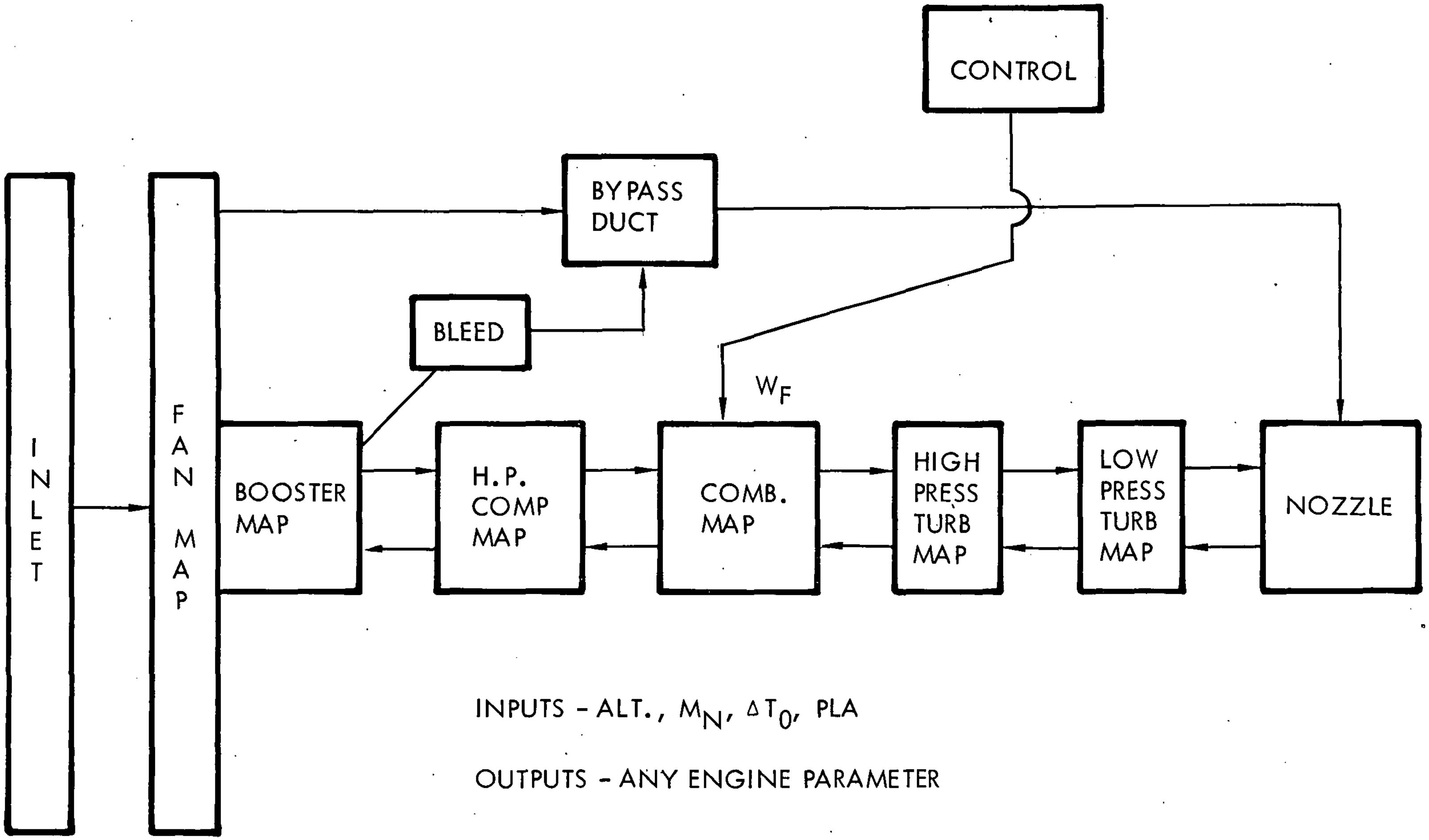
Eleven potential techniques were investigated. These techniques included seven variable geometry schemes, water injection, compressor bleed, increased turbine temperature limits, and decreased core compressor stall margin. The 11 techniques were also combined to form 19 combinations of variables that were also evaluated. These methods were investigated for their effect, both for improving acceleration and also as methods for spoiling thrust to initiate the acceleration from a higher speed, referred to herein as "approach thrust attenuation."

## ANALYTICAL METHOD

The engine and control system were simulated on an EAI 690 hybrid computer. The simulation then was employed to evaluate the techniques for improving jet engine transient performance. The modeling of the engine and controls was based on the computer modeling of the F101/GE13. The model also included the capability for synthesizing the variable geometry configurations being evaluated (see Figure 1).

### Engine Simulation

The engine simulation was set up with sufficient flexibility to permit the engine to be operated over the entire flight map and for various ambient temperatures. The ATT engine model was employed as the vehicle for the investigation. The ATT engine has the following characteristics and operating parameter limits:




INPUTS - ALT., $M_N$, $\Delta T_0$, PLA

OUTPUTS - ANY ENGINE PARAMETER

Figure 1. Engine Model.

| | | |
|---|---|---|
| • Bypass ratio | 6.14 | |
| • Thrust, SLS, hot day | 139 kN | (31,300 lbs) |
| • Airflow, SLS, hot day | 416 kg/sec | (918 lb/sec) |
| • Fan pressure ratio, SLS, hot day | 1.69:1 | |
| • Engine pressure ratio, SLS, hot day | 32:1 | |
| • Turbine inlet temperature, SLS, hot day | 1922° K | (3460° R) |
| • Fan rotor inertia | 63.8 $kgm^2$ | (1515 lb $ft^2$) |
| • Core rotor inertia | 12.13 $kgm^2$ | (288 lb $ft^2$) |
| • Thermal inertia (heat soak)* | 0.9 Seconds | |
| • Initial thrust level | 10% takeoff thrust | |

The following operating limitations were imposed on the engine during the investigation, except for investigations that involved that particular parameter.

| | | |
|---|---|---|
| • Turbine inlet temperature overshoot | 83.3° C | (150° F) |
| • Minimum transient core compressor stall margin | 9% | |
| • Shaft horsepower extraction | 112 kw | (150 hp) |
| • Compressor discharge bleed | 0% | |
| • Throttle rate | 1.745 rad/sec | (100°/sec) |

The engine variable geometry included:

- Variable booster bleed doors
- Variable core stators
- Two-position exhaust nozzle

*Thermal inertia (heat soak) is a result of the energy extracted from or added to the engine thermal cycle as the engine hot parts are heated or cooled during an engine acceleration or deceleration. The 0.9 second is the difference in acceleration time for a theoretical engine without any thermal mass and a real engine in which the hot parts require sufficient thermal energy to increase the acceleration time by 0.9 second.

The following variables were added for the analysis:

- Fan inlet guide vanes
- High pressure turbine area
- Low pressure turbine area
- Fan duct overboard bleed
- Water injection
- Compressor discharge bleed

The engine control system was designed with core rotor speed control at low rotor speeds (near idle) and with fan speed control at the higher rotor speeds. During steady-state operation, engine fuel flow was modulated to maintain rotor speed. During engine accelerations when the rotor speed error exceeded a preset value, fuel flow was limited by an acceleration fuel flow limit which was calculated as a function of core rotor speed, fan discharge temperature, core compressor static discharge pressure, and core compressor bleed pressure. Core stators were controlled to a function of core rotor speed and compressor inlet temperature. The fan booster bleed was controlled as a function of corrected fan and core speeds. The maximum turbine inlet temperature limit was imposed under all operating conditions. A maximum core compressor discharge pressure limit was also imposed at all times but was not a factor in this study since it was performed at approach Mach number. The simulated engine accelerations were conducted procedurally so that the calculated compressor stall margin was never less than 9%.

## Base Engine

The base engine, without any geometry modifications or changes, was set up to determine a reference acceleration time and rate. The FAA requirements state that an engine should be capable of being accelerated from flight idle or from not more than 15% of rated take-off power or thrust to 95% rated take-off power or thrust in not over five seconds, using only the bleed air and accessory loads necessary to run the engine. The simulated ATT engine was capable of accelerating from 10% take-off power to 95% take-off power in 4.4 seconds on a sea level static hot day (32° C/90° F), with 112 kw (150 horsepower) extraction (accessory load), 0.9 second heat soak, 1.75 rad/sec (100°/second) throttle rate, 83.3° C (150° F) temperature overshoot limit, 9% minimum stall margin, and no compressor bleed. On a standard day (15° C/59° F), the engine acceleration time was 4.2 seconds. Figure 2 shows the time responses of 12 parameters for the base engine. Both corrected and uncorrected core and fan speeds are shown, and engine fuel flow is included in both the right hand strip and the left hand strip. The throttle angle response (upper left) shows that the throttle is limited to 1.75 rad/sec (100°/second). The control mode strip chart was utilized to indicate the control mode in which the fuel control is operating. Prior to engine acceleration, the engine is on steady-state core

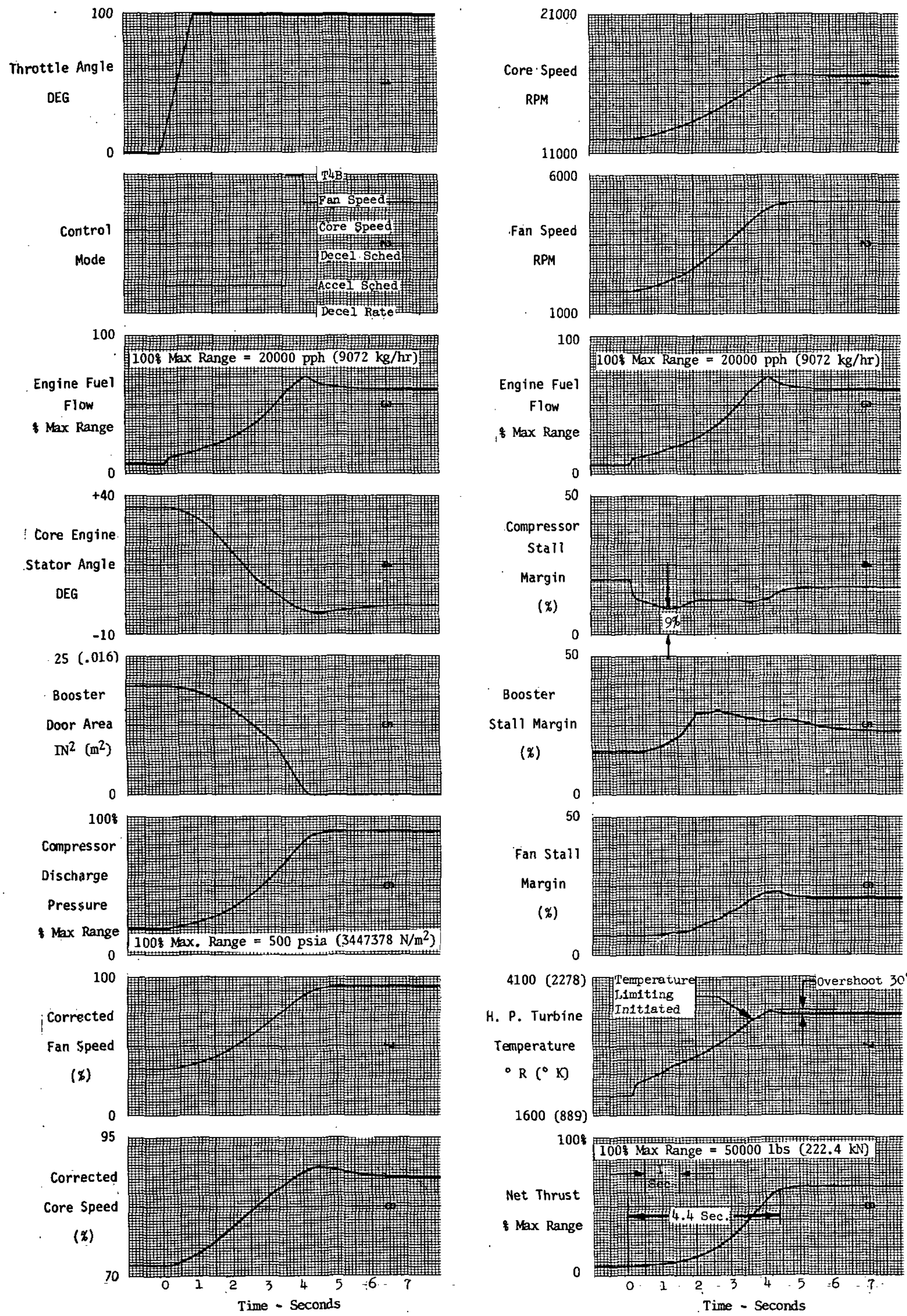



Figure 2. Base Run SLS + 31° C Day All Systems Nominal.

speed control. As the throttle is advanced, both rotors accelerate and the fuel control transfers to fan speed control for about 0.1 second and then transfers immediately to the acceleration schedule as the speed error increases. The fuel control remains on the acceleration schedule for approximately 3.4 seconds, at which time the measured turbine blade temperature begins to overshoot its limit, and the fuel control transfers to temperature limit control where it remains (0.5 second) until the temperature decreases to the limit and below. The control then returns to fan speed control and remains.

The effects of the fuel control as it changes control modes can be noted on the third strip chart in the left hand strip, engine fuel flow. Initially, while the engine is on fan speed control, the fuel flow increases rather rapidly until the control transfers to the acceleration fuel schedule, where it follows the acceleration schedule. It can be seen that as the control transfers to temperature limiting ($T_{4B}$), the rate of fuel flow increase is considerably reduced. As the thrust demand (or engine fan speed demand) is satisfied, the fuel flow is leveled and then decreased to maintain the steady-state thrust level. The remaining curves are engine variables and cycle parameters. Core compressor stall margin (fourth curve from the top on the right hand strip) was not permitted to fall below 9% by judicious limitation of the input demands to the engine. The high pressure turbine temperature (seventh curve in the right hand strip) shows the effects of the temperature limiting by changing to a slower rate of increase. The lower curve in the right hand strip shows the net thrust and was utilized to determine the merit of each technique investigated. The method of determining the transient or acceleration time should be noted. All accelerations, unless otherwise indicated, were initiated from 10% take-off thrust with a ramp demand to 100% thrust. The time was measured from the initiation of the demand until 95% take-off thrust was reached.

The SLS hot day conditions (32° C/90° F) were retained as the reference condition for the study, giving an acceleration time of 4.4 seconds as a base. The various techniques were then evaluated relative to the potential for reducing the engine acceleration time from 4.4 seconds. The merit of a particular technique was determined by calculating the percentage reduction in acceleration time from 4.4 seconds.

The base power of 10% rated take-off thrust was utilized for all of the acceleration studies. This base thrust level was selected on the basis of preliminary data on the Boeing 767-640 aircraft (see Figure 3). The 10% thrust level corresponds to approximately a 0.131 radian ($7\frac{1}{2}$°) glide slope and a 0.524 radian (30°) flap setting for the aircraft. It also corresponds to a glide angle of slightly greater than 0.105 radian (6°) with a 0.384 radian (22°) flap angle (Ref. 3). Ten percent thrust is also approximately the flight idle power setting and would produce the lowest in-flight noise from the rotating machinery (unless flight idle is reduced). It does, however, result in a more pessimistic acceleration time (e.g. 4.4 seconds for the base engine when accelerating from a 10% thrust level as compared to 3.4 seconds when accelerating from an initial 15% thrust level) with all other conditions identical. Figure 4 shows the variation in response as a function of initial power setting. It is this fact which provides the motivation for the approach thrust attenuation techniques.

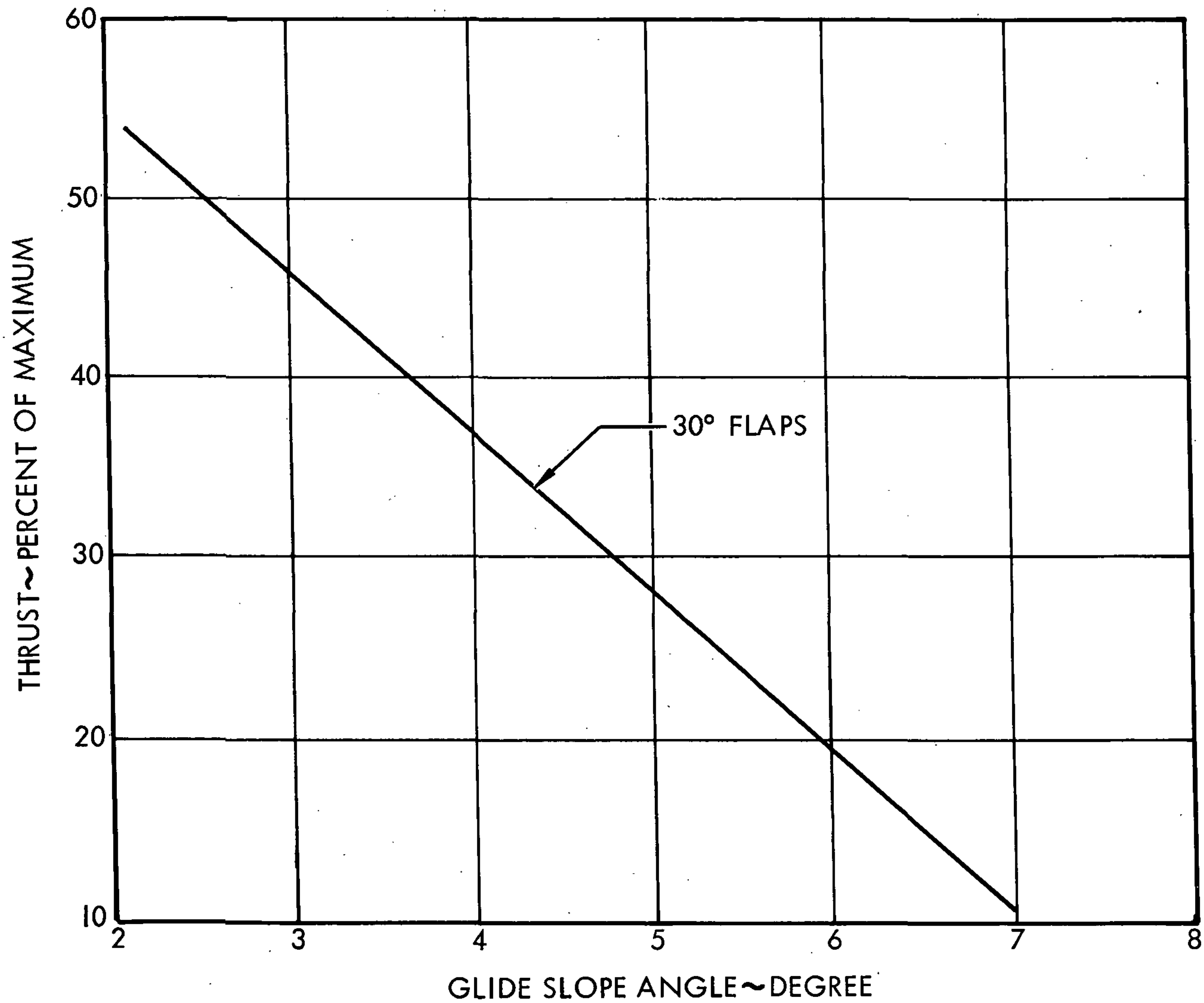



Figure 3. Approach Power Setting.

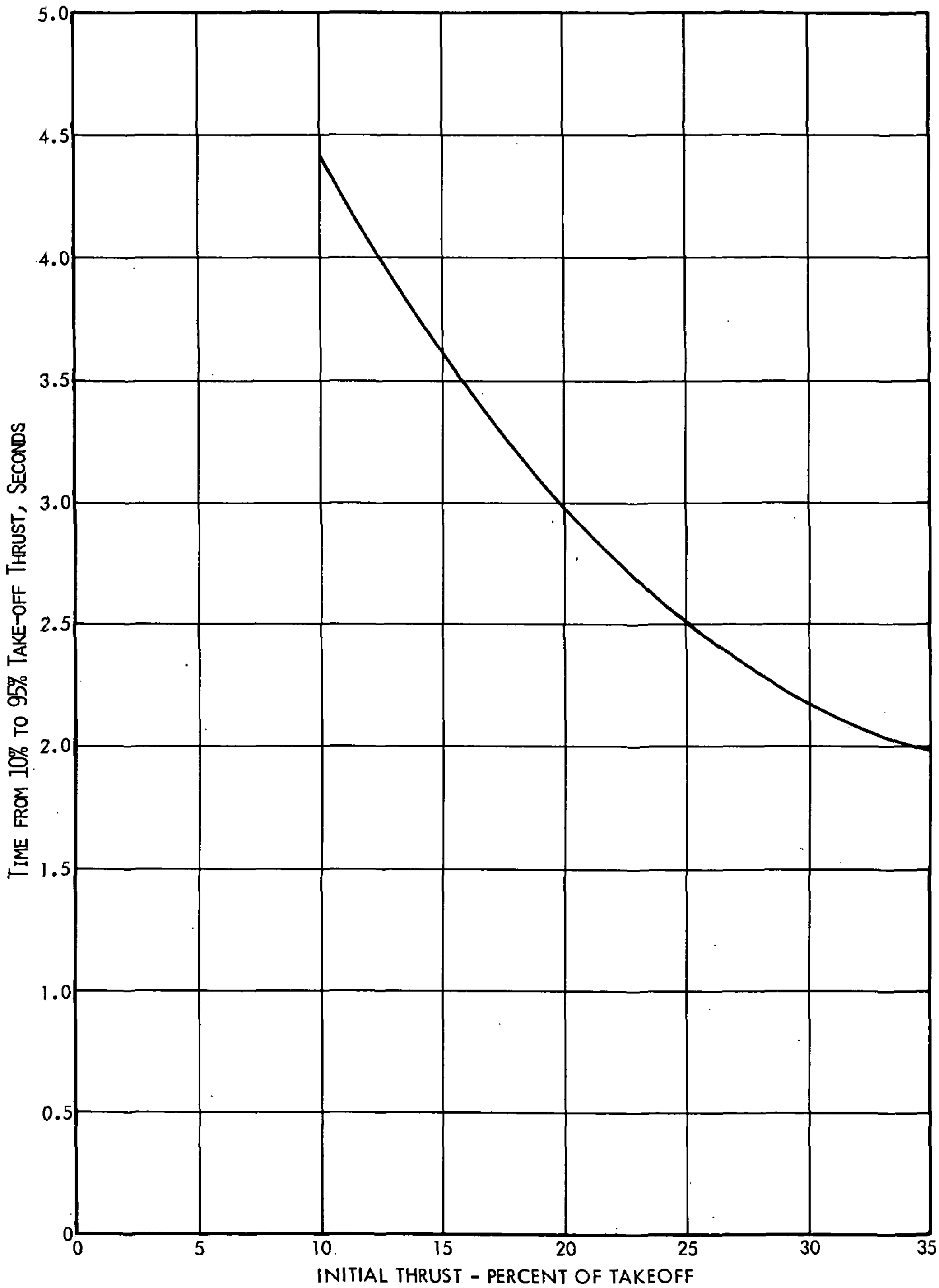



Figure 4. Effects of Initial Power on Response Time.

General Electric CF6 engine. Because the General Electric CF6 engine is a commercial, high bypass, turbofan engine, it was used as a basis of comparison for the mathematical model of the ATT engine.

Acceleration transients were made on both the CF6-6 and the CF6-50 digital computer models with conditions similar to those imposed on the ATT model [i.e., sea level static standard day (15° C/59° F), 112 kw (150 horsepower) shaft horsepower extraction, zero compressor bleed, and with throttle bursts from flight idle, 30%, and 50% rated thrust]. The thrust transients as a function of time are shown in Figure 5 for the CF6-6 and in Figure 6 for the CF6-50. Table I compares the computer model data for the CF6-6 and the CF6-50 with the ATT model data.

Table I. Acceleration Time in Seconds.

| Engine | Flight Idle (SLS-Standard Day) | From 30% | From 50% |
|---|---|---|---|
| CF6-6 | 3.7 (14% FN) | 2.9 | 1.9 |
| CF6-50 | 5.0 (11% FN) | 3.3 | 2.2 |
| ATT | 4.2 (10% FN) | 2.2 | --- |

The models were not optimized for fast accelerations. Note that the CF6-50 (Figure 6) has no overshoot; thus, the acceleration could have been improved merely by increasing fuel flow schedule. The CF6-6 (Figure 5) does show some overshoot and, hence, has been optimized to a greater degree than the CF6-50.

The acceleration times for 180 CF6-6 production engines are shown in Figure 7. The average acceleration time for the 180 engines was 3.94 seconds as compared to 3.8 seconds for the computer model when run at the same conditions as the actual engine accelerations.

## Variable Geometry

Most of the 11 variables were investigated both as methods for improving the acceleration rate and as a method of thrust attenuation to allow acceleration from a higher rotor speed. Figure 8 shows nine of the variables and their locations on the engine.

Rapid acceleration. The following engine variables were investigated to determine their effect on engine acceleration rate.

- Core stators - opened 0.0872 radian (5°) during acceleration.
- Fan IGV - opened 0.0872 radian (5°) during acceleration.
- Nozzle area - opened 10% from nominal during acceleration.
- Booster bleed door - closed completely during acceleration.

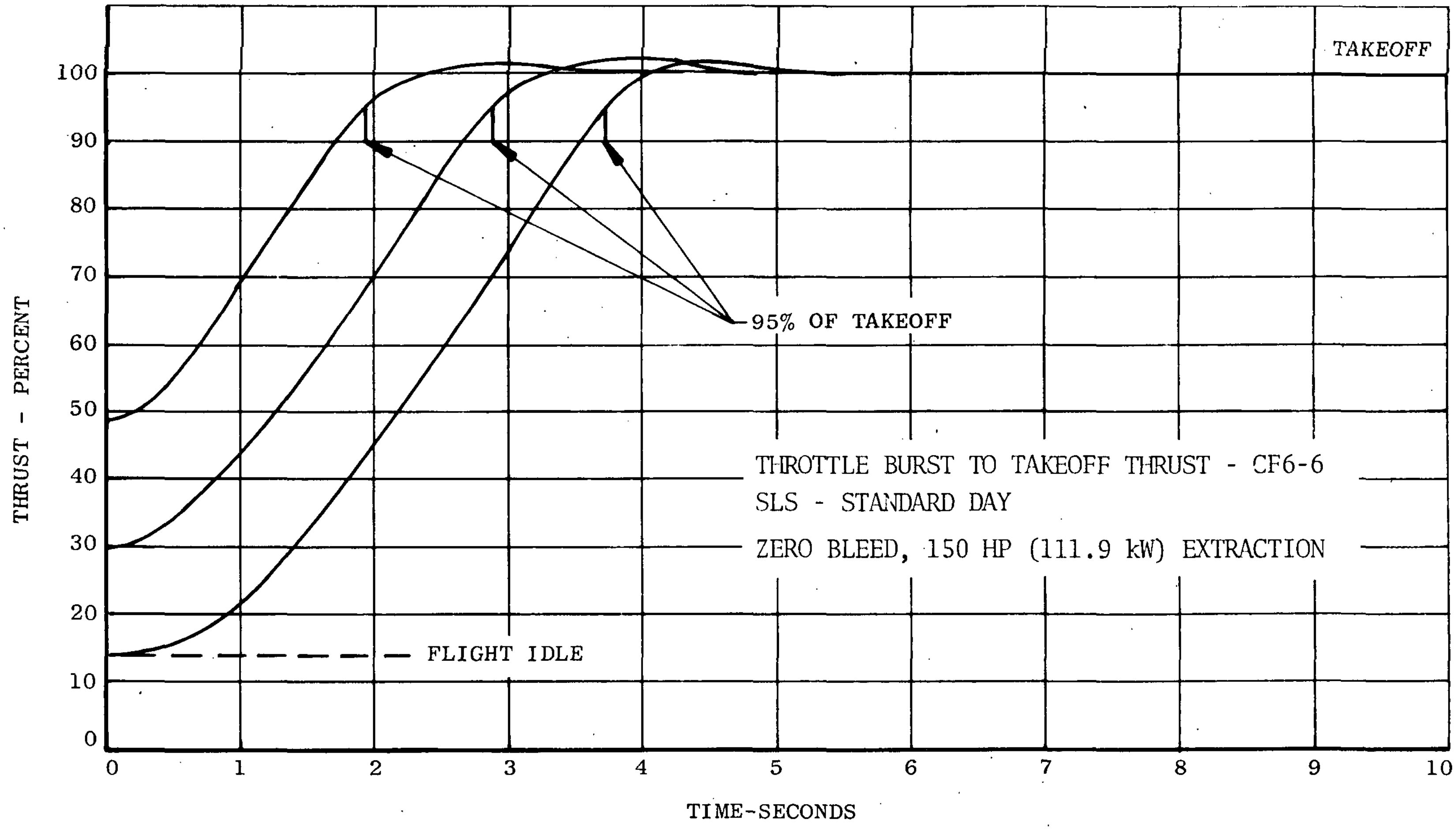



Figure 5. Throttle Burst to Take-Off Thrust, CF6-6.

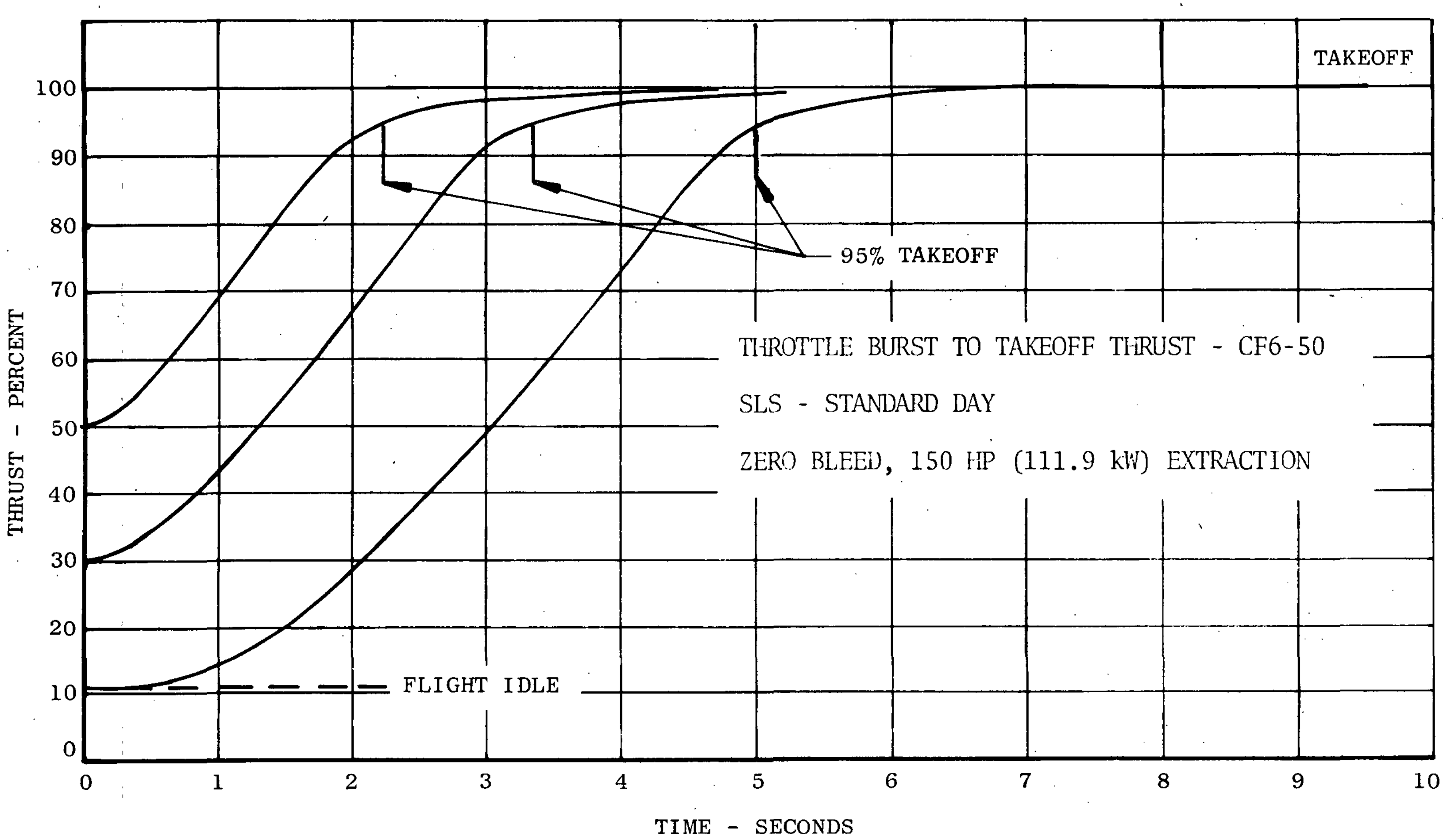



Figure 6. Throttle Burst to Take-Off Thrust, CF6-50.

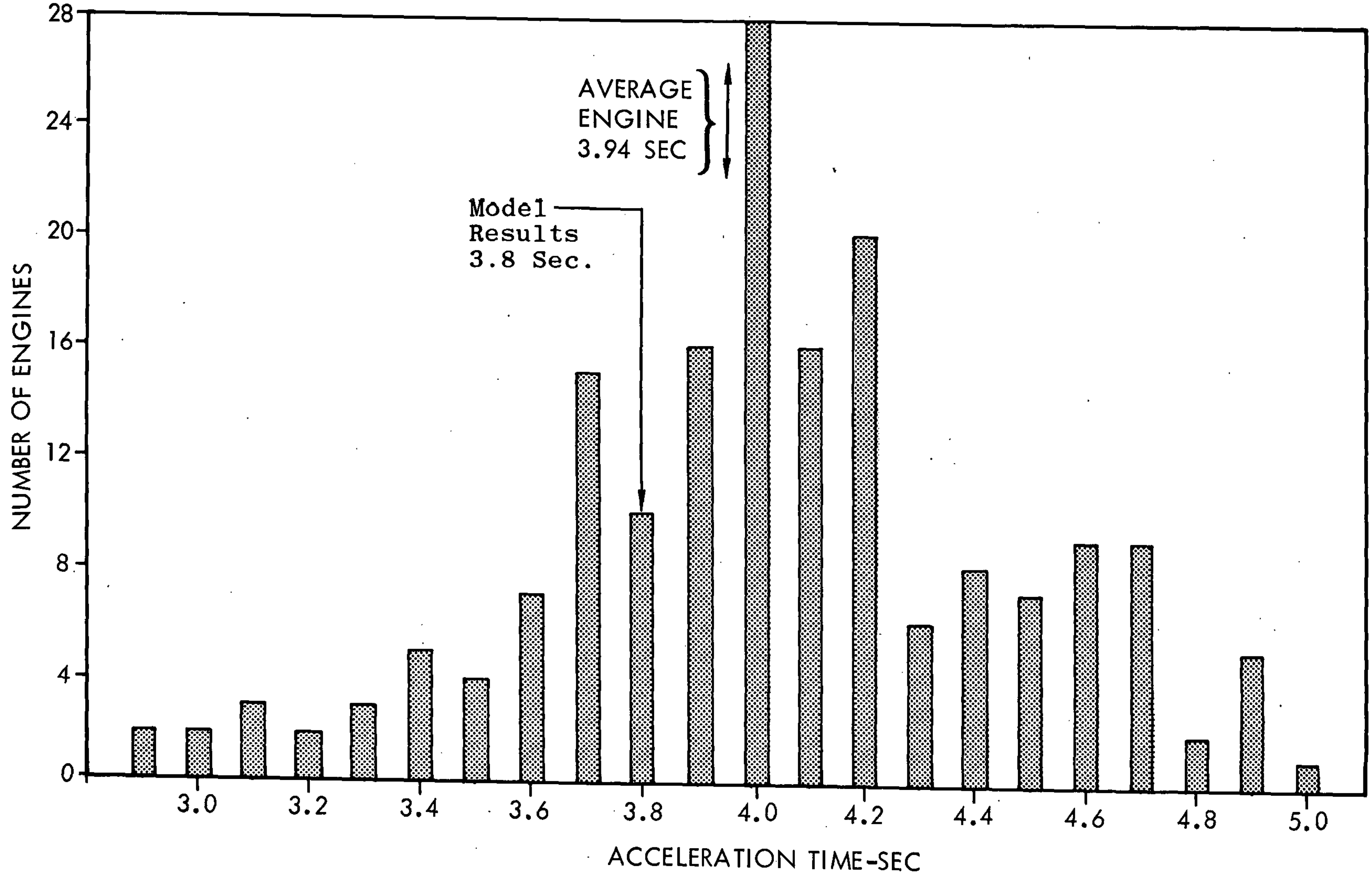



Figure 7. Acceleration Times, CF6-6 Production Engines at Sea Level, Time to 95% $N_1$.

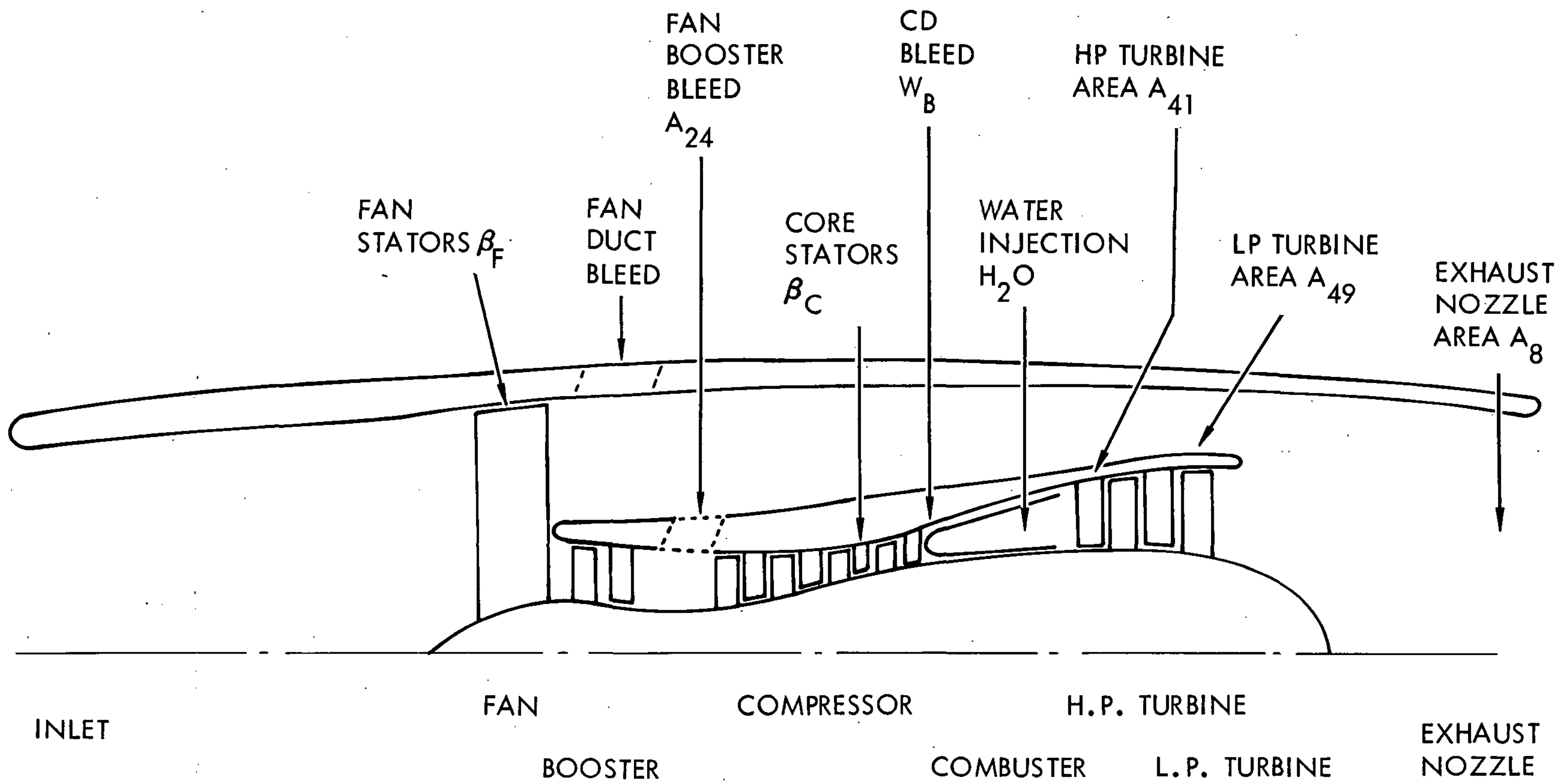



Figure 8. Engine with Variables.

- Low pressure turbine area - opened 5% from nominal during acceleration.

- High pressure turbine area - opened 5% from nominal during acceleration.

- Water injection - 2% water injected at combustor inlet during acceleration.

- Compressor discharge bleed - 5% during acceleration.

Opening the high pressure turbine area 5% from nominal during the acceleration provided the best results for any single variable with a 26.8% improvement in acceleration time. However, 3% water injection at the combustor inlet was nearly as effective, providing a 24.6% improvement.

These same variables were then combined in pairs with four combinations analyzed. The best combination for improving acceleration utilized 2% water injection at the compressor discharge and opening the high pressure turbine area 5% more than nominal for engine acceleration. This procedure resulted in a 36% improvement in acceleration rate.

Approach thrust attenuation - higher rotor speed. Many of the same variables were also utilized to increase the base engine speed prior to the transition from the initial glide slope. The variables and the manner in which they were utilized are indicated below. The influence of thrust level prior to thrust acceleration on transient time is shown in Figure 4.

- Core stators - Closed 0.0872 radian (5°) from nominal during the approach and then returned to nominal schedule for engine acceleration.

- Core stators - Closed 0.0872 radian (5°) from nominal during the approach and then opened 0.0872 radian (5°) beyond the nominal scheduled for the engine acceleration.

- Nozzle area - Opened 30% from nominal during the approach and then returned to the nominal schedule for the engine acceleration.

- High pressure turbine area - Closed 5% from nominal during the approach and then returned to nominal schedule for the acceleration.

- Low pressure turbine area - Closed 5% from nominal during approach and returned to nominal for the acceleration.

- Booster bleed door - Full open during the approach and then returned to nominal schedule for the acceleration.

- Compressor discharge bleed - 5% bleed during approach and then shut off for engine acceleration.

- Compressor discharge bleed - 5% bleed during approach and then shut off for engine acceleration.

- Compressor discharge bleed - 5% bleed during approach and continued 5% bleed during acceleration.

Opening the nozzle area 30% from nominal during approach provided a 12% improvement in acceleration time. The most gain in transient performance of any of the single variables used to increase the engine speed prior to acceleration was obtained with the sustained 5% compressor discharge bleed which provided a 16.4% reduction in acceleration time. Four combinations of the above techniques were also evaluated. The most improvement, 30%, was obtained by a combination of closing the core stators 0.0872 radian (5°) and opening $A_8$ 30% during approach, and then returning them to schedule for engine acceleration with a 5% compressor discharge bleed both during the approach and acceleration.

The amplitude of the variation in the engine variables, although selected somewhat arbitrarily, was based on values that were realistic and capable of being achieved. For example, it may be possible to increase the core stator angle beyond 0.0872 radian (5°), but the mechanical and aerodynamic impact should be analyzed before larger angles are used. The 30% variation in exhaust nozzle area should be completely realistic as are the 5% compressor bleed and the 2% water injection. The booster bleed door does affect the booster stall margin when closed and, hence, should be reviewed. Because it does have a relatively small effect, it was not investigated further at this time. The change in both high pressure and low pressure turbine area by 5% also has potential, but again the impact on the aerodynamic and mechanical considerations must be investigated before larger perturbations are considered. In the case of the variable turbine area, the problems and penalty of mechanizing a variable area system must be evaluated and a trade study conducted to weigh the gains and penalties of either system.

Approach thrust attenuation techniques will generate more high frequency noise than the rapid thrust techniques because of the higher rotor speeds. This high frequency noise will lend itself to treatment of the engine nacelle better than the low frequency noise. Hence treatment of the nacelle and thrust attenuation may offer an attractive approach. The use of the flow diverters or thrust reversing techniques to spoil thrust were considered but not investigated further because it resulted in higher approach noise.

<u>Combination of approach thrust attenuation and rapid acceleration</u>. Techniques which provided improved transient performance by raising the engine rotor speed prior to acceleration were, in turn, combined with those techniques which operated directly on improving the acceleration performance. Seven such combinations were analyzed. An involved combination of four functions was investigated and found to reduce acceleration time by 36.3%. The four functions are: core stators closed 0.0872 radian (5°), nozzle area opened 30%, 5% core discharge bleed, and 2% (of core engine airflow) of water injection all during the initial glide slope approach. At acceleration, the nozzle area and core stators were returned to the nominal schedule, 5% core bleed was maintained, and 2% water injection was initiated.

Temperature and stall limit variation. Throughout most of the investigation, the turbine inlet temperature overshoot limit was set at 83.5° C (150° F), and the core compressor stall margin was not permitted to be lower than 9%. However, during one part of the investigation, the maximum temperature and minimum stall limits were permitted to be exceeded to determine their effects on the acceleration time (see Figures 9 and 10). Also, compressor discharge bleeds as high as 7.5% and water injection rates up to 4% of compressor airflow were simulated.

## EVALUATION AND RESULTS

The effects of the 11 variables, as they were applied individually, are described below. Each technique is discussed with respect to rapid acceleration and thrust attenuation where both are applicable. The effectiveness and the manner by which the variable served to alter the transient response are described.

Some of the more promising combinations of variables are also discussed and compared.

### High Pressure Turbine Temperature Limit

The purpose of the turbine blade temperature limit is to reduce or prevent transient temperature overshoot and to prevent steady-state operation above a maximum temperature. Turbine blade temperature is sensed with an optical pyrometer and the signal is used to decrease fuel flow when the measured temperature exceeds the preset limit, thus protecting the turbine from high temperature operation.

Transient temperature overshoot during an acceleration is further reduced by the lead compensation network incorporated in the fuel control, thus minimizing the temperature overshoot by decreasing fuel flow below the acceleration schedule.

Raising the temperature limit will permit more fuel to be supplied to the engine, resulting in a faster acceleration. This improved acceleration is achieved at the expense of more temperature overshoot, higher turbine temperature, and decreased turbine life. With the base configuration, the last 0.5 second of the 4.4 second acceleration is on $T_{4B}$ control. Allowing more overshoot can only reduce this portion of the acceleration. The effect of $T_{4B}$ overshoot on acceleration time is shown in Figure 9. If this technique is used in conjunction with one which increases the percent of $T_{4B}$ controlled acceleration time (for example, compressor discharge bleed), then more improvement would be obtained. The main disadvantage of increasing $T_{4B}$ limit is reduction of turbine life, since it permits the turbine to operate at higher temperature during acceleration.

### Acceleration Fuel Schedule

The acceleration fuel schedule is a function of core speed, compressor discharge pressure, and compressor inlet temperature. Its purpose is to

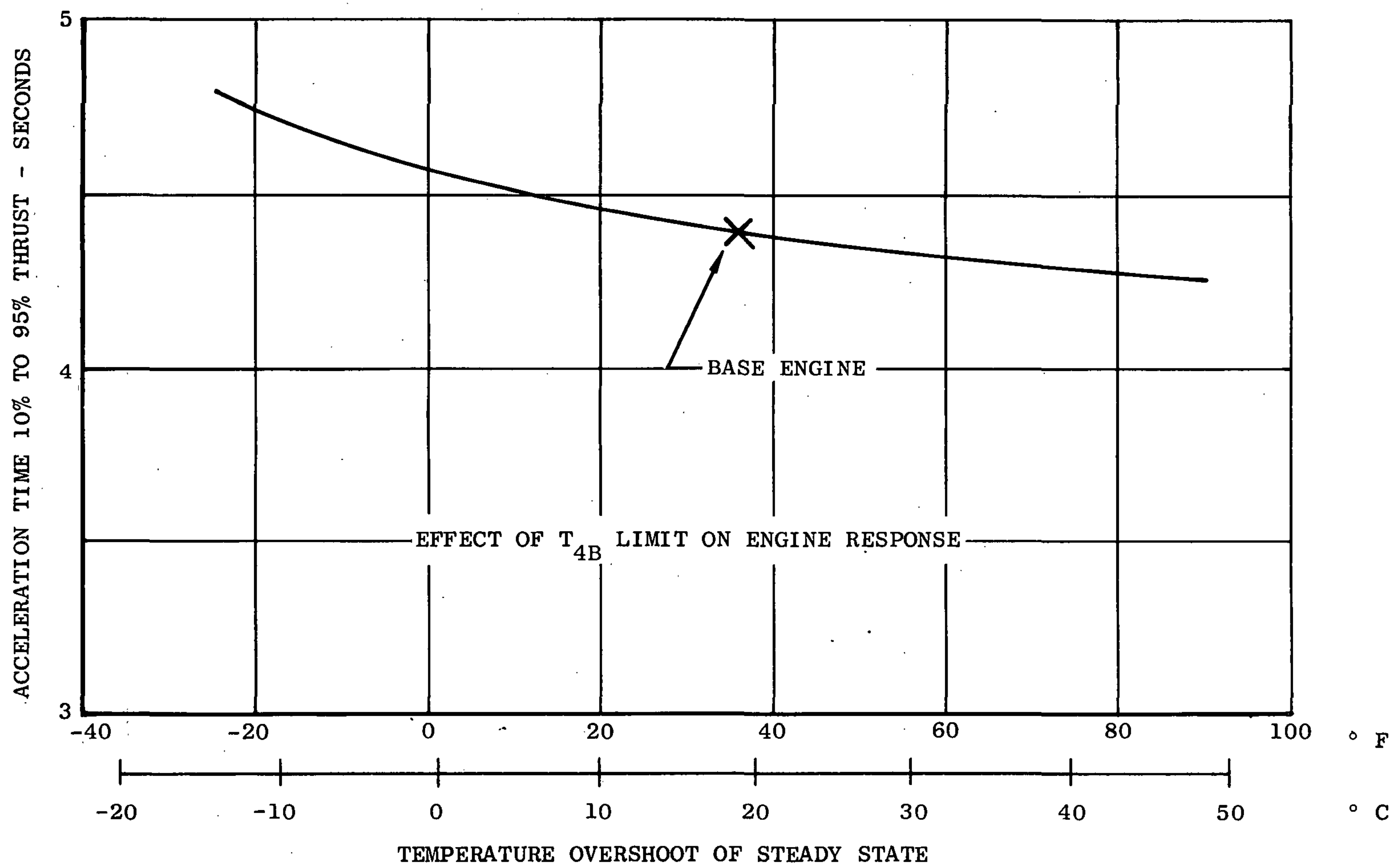



Figure 9. Effects of $T_{4B}$ Limit on Engine Response.

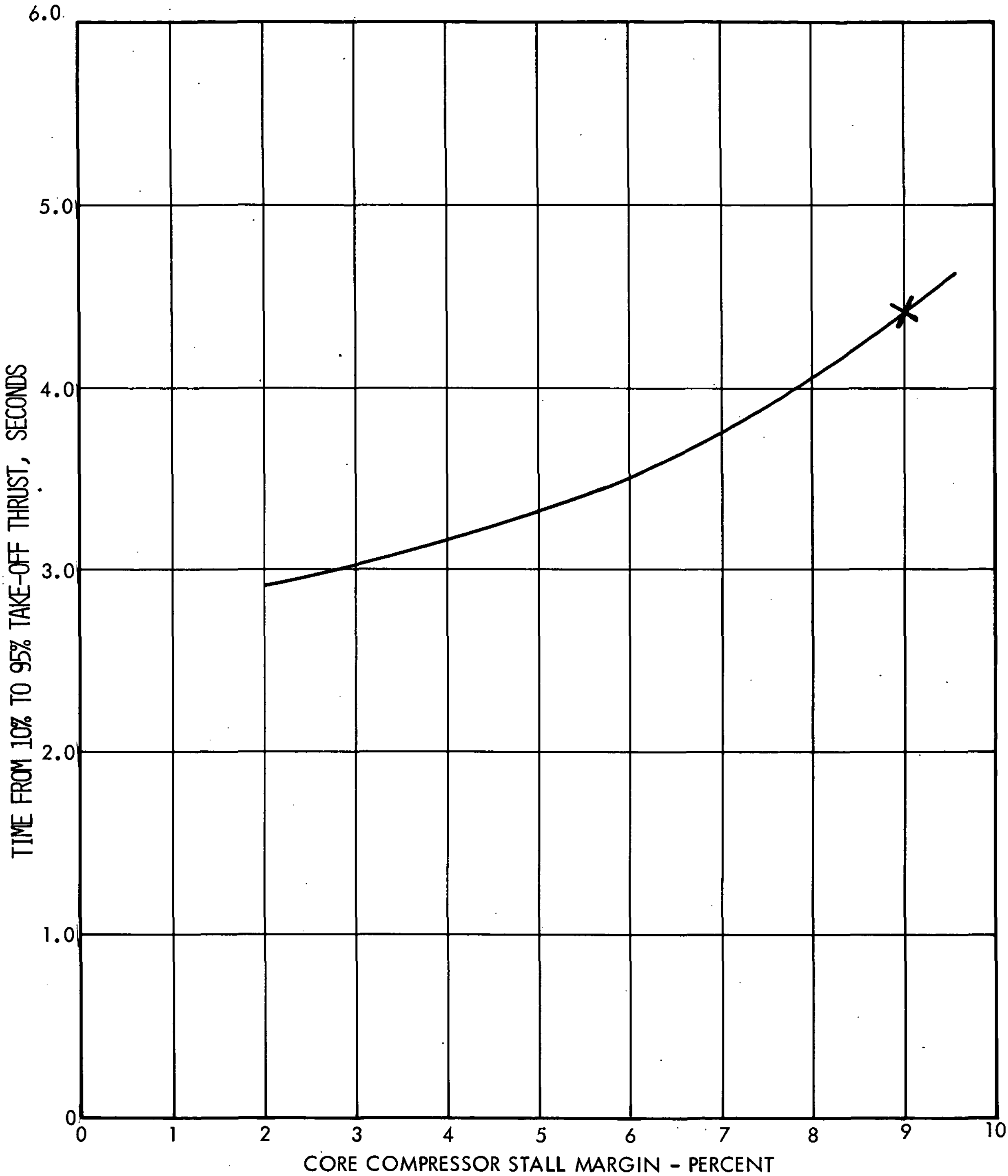



Figure 10. Response Time Varied by Increasing the Acceleration Fuel Schedule, with Resultant Loss in Stall Margin.

maintain compressor stall margin during transients while providing sufficient fuel flow to accelerate the engine.

Increasing the acceleration fuel schedule decreases the acceleration time by increasing the energy available. However, the compressor transient operating line moves closer to the stall line, reducing the stall margin. The rate of change of turbine temperature is higher, resulting in larger temperature overshoot and a larger percent of time on the $T_{4B}$ control.

Figure 10 shows the effect on acceleration time of utilizing more stall margin (by increasing the acceleration fuel schedule). It should be noted that stall margin cannot be used completely. Allowance must be made for engine and control system tolerances, compressor pressure and flow distortions, etc., so that Figure 10 illustrates the trend rather than absolute values. A practical approach would require designing more stall margin into the compressor.

## Compressor Discharge Bleed

Continuous bleed. Compressor discharge bleed lowers the compressor discharge pressure, lowering the transient (and steady-state) operating line, thus increasing stall margin. This allows more fuel to be supplied for the same minimum stall margin (9%), producing a faster acceleration. The additional work done by the compressor uses only part of the increased available energy.

The acceleration fuel schedule was adjusted to maintain minimum stall margin at its nominal value (9%).

The disadvantage of this scheme is higher turbine temperature. If compressor discharge bleed exceeds 5%, the $T_{4B}$ limit becomes the steady-state control on a hot day.

Because steady-state thrust decreases with bleed, core speed must be increased to provide the 10% thrust starting value (before acceleration). Figure 11 shows the effect of bleed on acceleration time.

Approach thrust attenuation. The higher core speed required with bleed to provide a given thrust can be used to an advantage. If bleed is stopped as the acceleration is initiated, a faster acceleration is obtained because the required change in core rpm is less.

The effect is not large (e.g., 5% bleed before acceleration, switched to zero as acceleration commences improves the acceleration time by 6%).

## Fan Duct Overboard Flow

Duct overboard flow during acceleration. Fan duct overboard flow reduces fan pressure ratio without decreasing low pressure turbine work, thus increasing unbalanced torque and allowing the low pressure spool to accelerate faster.

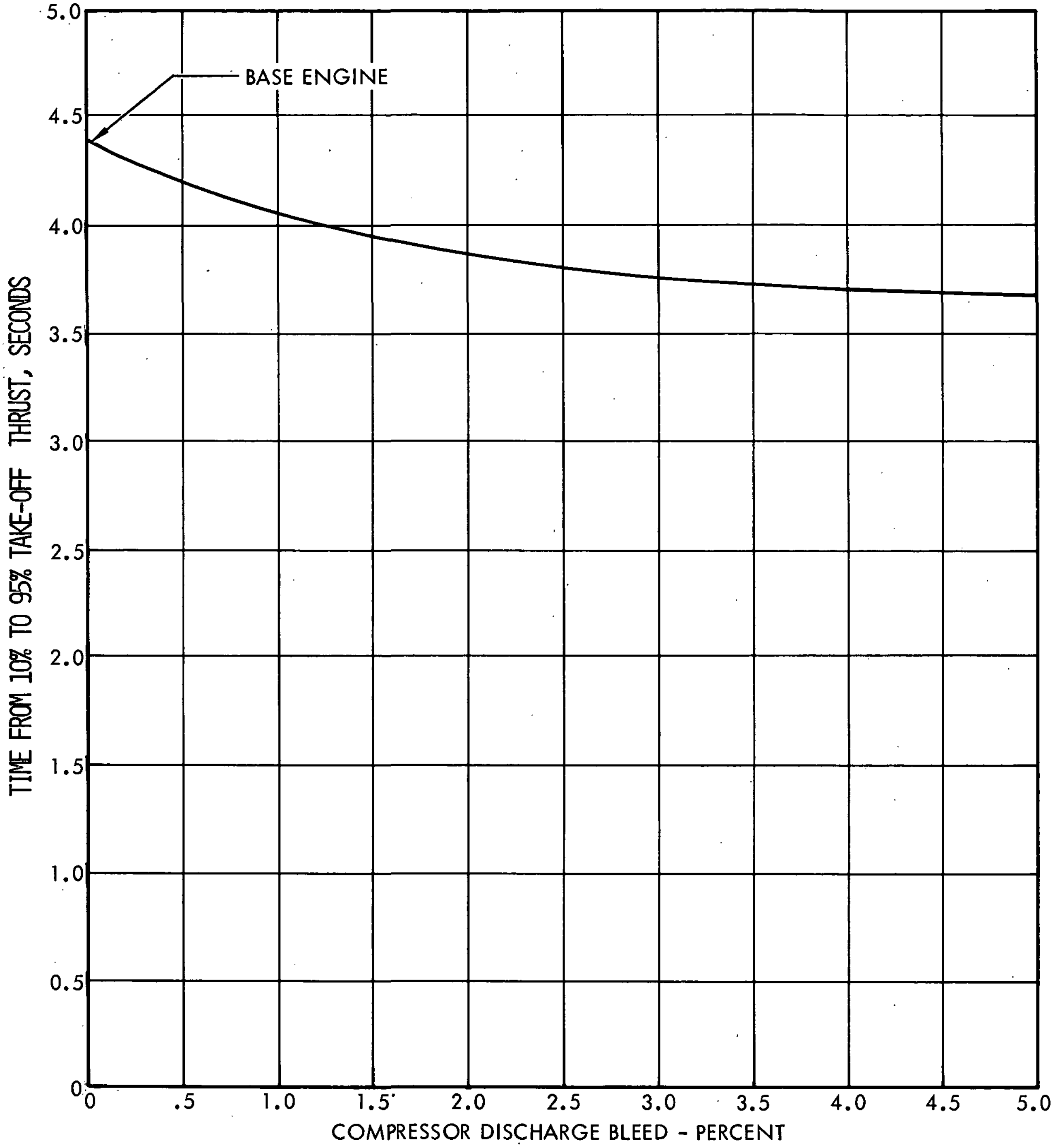



Figure 11. Effects of Bleed on Engine Response.

Figure 12 shows the effect of fan duct bleed on acceleration time.

Approach thrust attenuation. Core speed and fan speed are higher than base values for the same thrust. Thus, if overboard flow is shut off as the acceleration is initiated, a smaller change in rpm is required to achieve final thrust.

Acceleration time is reduced by 6% if 5% fan duct overboard flow during approach is reduced to zero at the start of the acceleration. Larger increases (75%) in fan duct overboard flow are feasible, thus producing a correspondingly larger decrease in acceleration time.

## Fan Inlet Guide Vanes

Closed during acceleration. Closing the fan inlet guide vanes reduces fan airflow, thereby reducing fan work for the same low pressure turbine work and enabling the low pressure spool to accelerate faster. However, thrust is reduced so that higher rpm is required to provide final thrust.

The change in flow is small (for this model), and no improvement in acceleration time was obtained with 0.0872 radian (5°) change in vane angle.

Approach thrust attenuation. Because of the small effect of fan inlet vane angle on the cycle (fan pressure ratio is only 1.07 at the 10% thrust point), thrust attenuation with up to a 0.0872 radian (5°) closure shows no improvement in acceleration time.

## Booster Bleed

Reduced bleed during acceleration. The booster bleed door schedule allows a bleed area of 0.013 $m^2$ (19 $in^2$) at the zero Mach number, 10% thrust base point. If the door is closed, compressor stall margin increases slightly, allowing more fuel to be used during the acceleration.

Normally, as rpm increases, the booster bleed door area is reduced to aero. Consequently, the effect of zero bleed during the whole acceleration has less effect as rpm increases.

A reduction of 4% in acceleration time is obtained by using zero booster bleed during the acceleration.

Approach thrust attenuation. As modeled, the maximum booster bleed door area is 0.043 $m^2$ (67 $in^2$). With this door area at the 10% thrust level, a slightly higher rpm is obtained.

With 0.043 $m^2$ (67 $in^2$) door area before acceleration, switching back to nominal at the start of the acceleration results in a negligible 1% reduction in time.

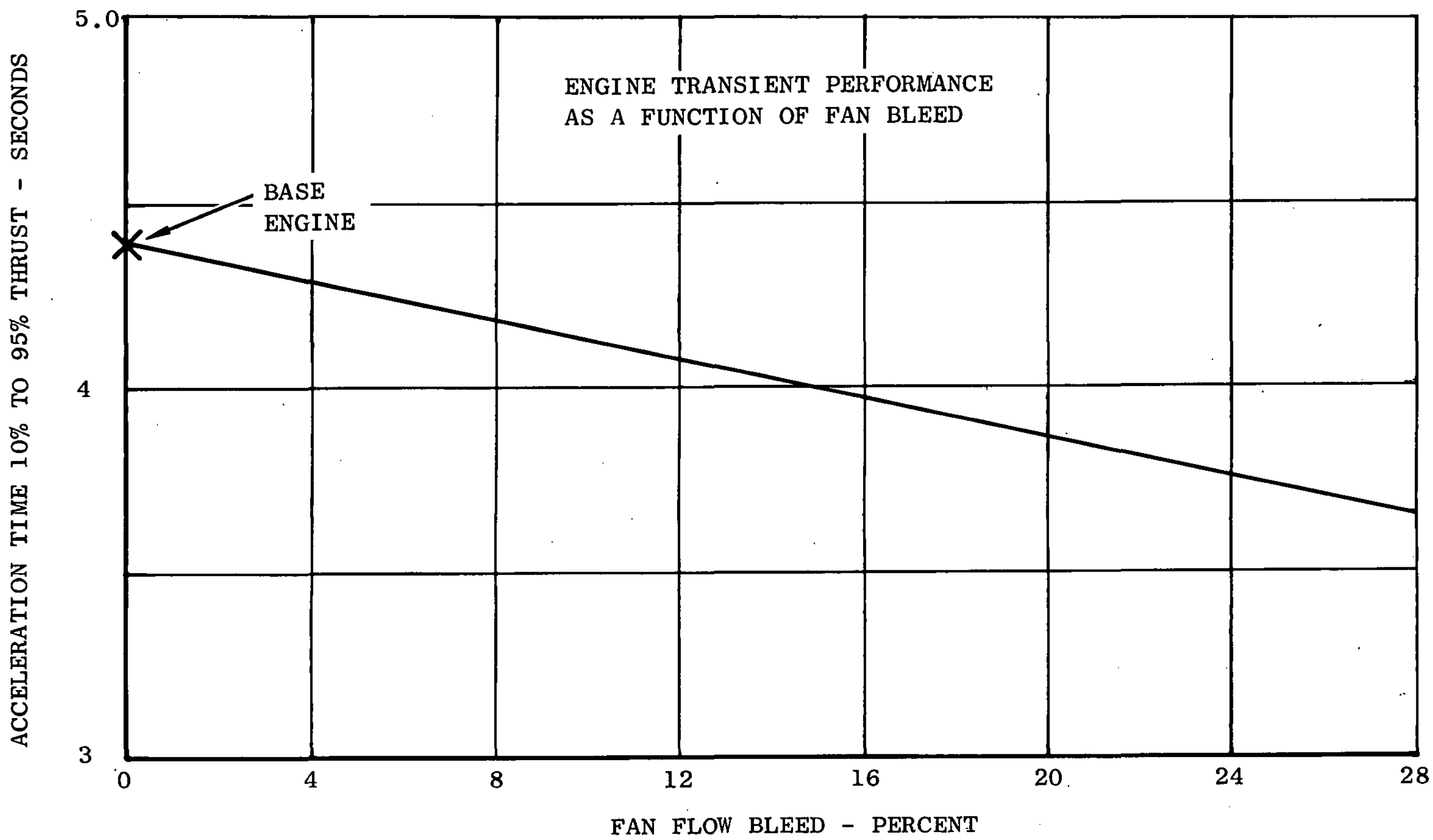



Figure 12. Acceleration Time as a Function of Fan Bleed.

## Core Stators

Open during acceleration. Opening the core stators beyond their nominal schedule to increase core airflow also reduces the transient stall margin. The reduction in acceleration fuel flow required to restore stall margin to nominal produces an acceleration longer than the base time.

Approach thrust attenuation. Closing the core stators below their nominal position decreases core airflow, requiring higher rpm to maintain approach thrust (10% of take-off thrust). Consequently, returning the stators to nominal as the acceleration is commenced will reduce acceleration time.

With the core stators 0.0872 radian (5°) more closed than normal at 10% thrust and returned to nominal schedule at the start of the acceleration, acceleration time is decreased 9%.

In view of the availability of variable core stators, this is a promising scheme.

## Exhaust Nozzle Area

Increased nozzle area during acceleration. The model has mixing of high pressure and low pressure exhaust flows so that changing nozzle area effects both the high and low pressure systems. Increasing exhaust nozzle area has several effects on the cycle, but has no significant improvement in acceleration time. Compressor stall margin increases, allowing more acceleration fuel flow. However, thrust at a given rpm is lower, requiring higher rpm to attain final thrust.

With the exhaust nozzle increased 10%, a 1% reduction in acceleration time is obtained.

Approach thrust attenuation. Since higher rpm is required to maintain approach thrust, a reduced acceleration time is obtained if the nozzle area is returned to nominal at the start of the acceleration. The proposed nozzle would allow up to 30% change in area and, with a 30% increase used during approach and returned to nominal at the start of the acceleration, a 12% reduction in acceleration time is obtained.

If the variable exhaust nozzle is incorporated, it should be designed to allow the thrust spoiling mode of operation when rapid accelerations are necessary.

## High Pressure Turbine Nozzle Diaphragm

Increased area during acceleration. The most significant effect of increasing the high pressure turbine nozzle diaphragm area ($A_{41}$) is the reduction of compressor discharge pressure. This lowers the transient (and steady-state) operating line, increases stall margin, and allows more acceleration fuel to be added for the same minimum transient stall margin (9%).

Figure 13 shows the effect of $A_{41}$ on acceleration time, while Figure 14 compares the response with an open $A_{41}$ area to the base engine response. Although this scheme is very effective, it is difficult to mechanize. Further, the addition of a variable $A_{41}$ system is estimated to reduce turbine efficiency by approximately 1%.

Approach thrust attenuation. If the high pressure turbine nozzle diaphragm area ($A_{41}$) is reduced from nominal, higher rpm is needed to maintain thrust. Restoring $A_{41}$ to nominal as the acceleration is commenced produces a small improvement in acceleration time. Specifically, a 5% smaller $A_{41}$ during approach, restored to nominal as the acceleration is commenced, reduces acceleration time by 1%.

### Low Pressure Turbine Nozzle Diaphragm Area

Increased area during acceleration. Increasing the low pressure turbine nozzle diaphragm area ($A_{49}$) produces a small gain in compressor stall margin. The acceleration fuel schedule can then be increased so that stall margin is decreased to nominal (9%). Specifically, an $A_{49}$ increase of 5% produces a 5% decrease in acceleration time.

A comparison of increasing the high pressure turbine area vs. the low pressure turbine area shows that a 5% increase in high pressure turbine area is five times as effective as a 5% increase in low pressure turbine area.

Approach thrust attenuation. Because of the relatively small effect on the cycle, decreasing $A_{49}$ during approach followed by a return to nominal at the start of the acceleration produced no improvement in acceleration time.

### Water Injection

Addition of water in the region of the combustor during an acceleration has several cycle effects, the most significant of which is increased turbine mass flow. Although there is a loss in compressor stall margin, its effect is small compared with the increase in unbalanced torque resulting from the higher turbine mass flow.

The effect of combustor water injection in terms of % of compressor airflow on acceleration time is shown in Figure 15. Some of the reduction in effectiveness at the higher levels of injection is due to the acceleration fuel schedule reaching an aribtrary limit.

The water also can be added at engine inlet or at the compressor inlet. However, the compressor aerodynamic characteristics are changed and, at cool ambient conditions, injection is limited to 2% or less due to saturation.

### Combinations

The combination of variables begins with run number 11, as shown in Figure 16. There were several types of combinations employed during this evaluation. A single variable was used both for approach thrust attenuation

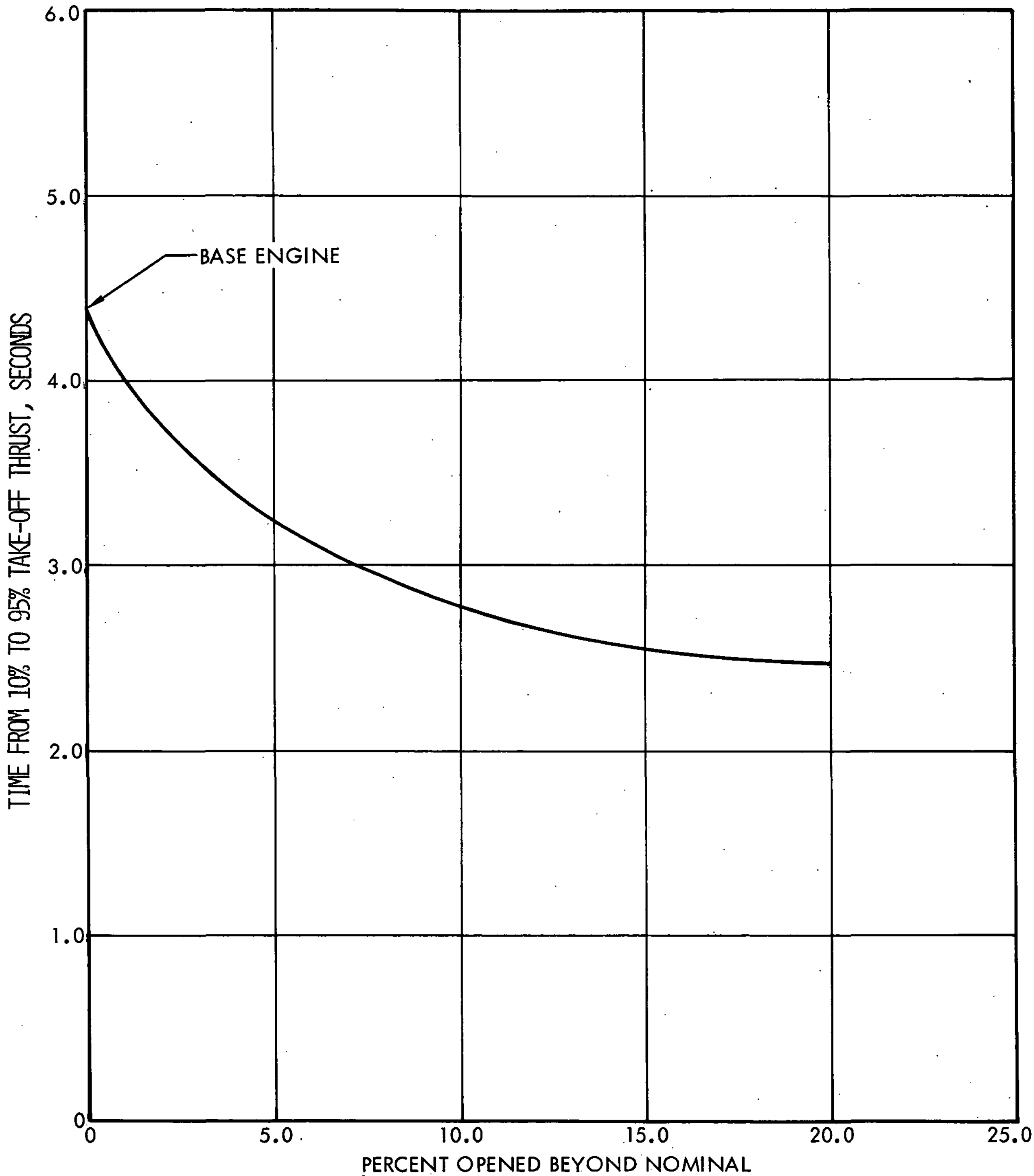



Figure 13. Effects of Opening High Pressure Turbine Area on Engine Response.

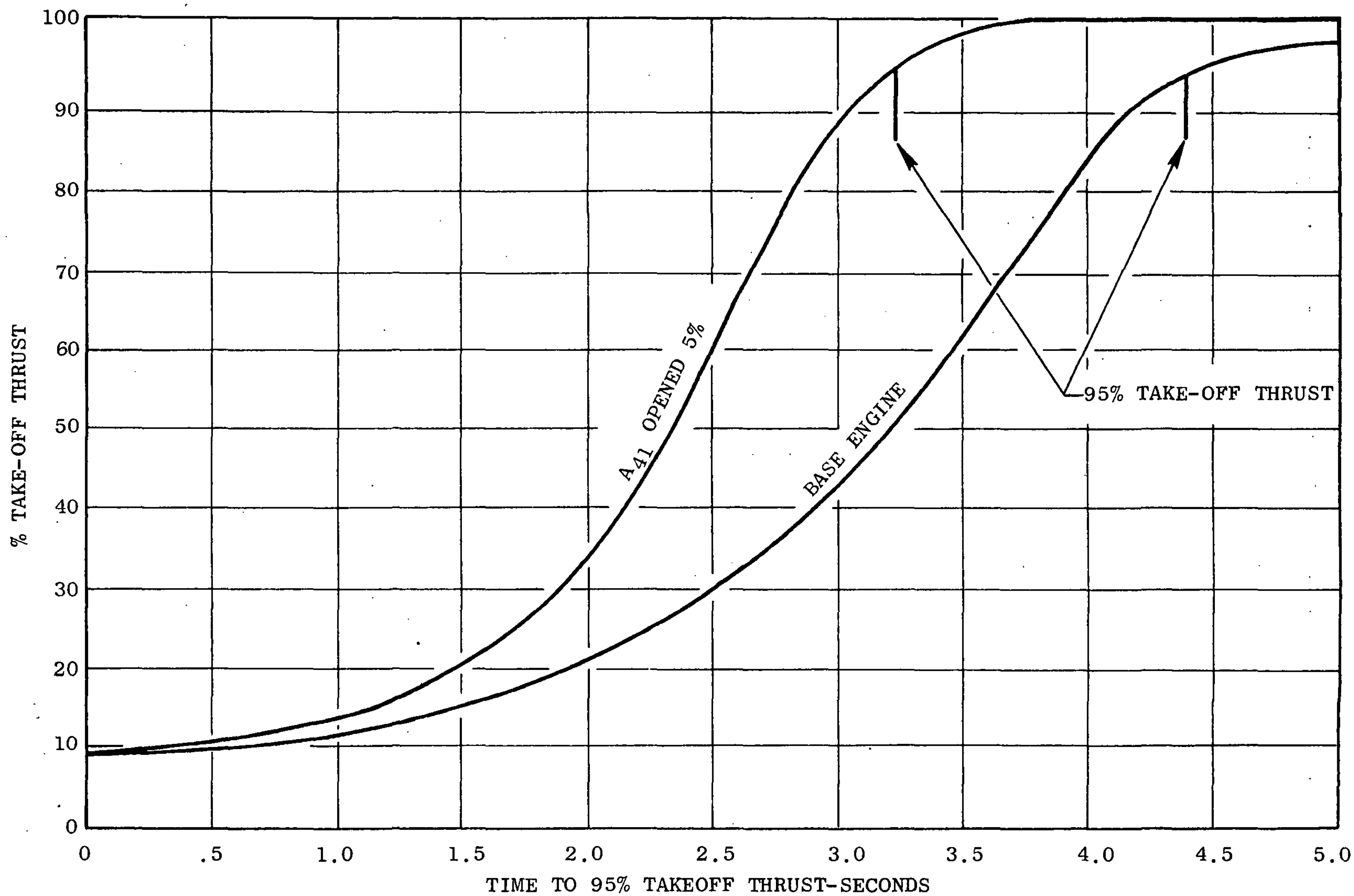



Figure 14. Engine Response with Open HP Turbine Area.

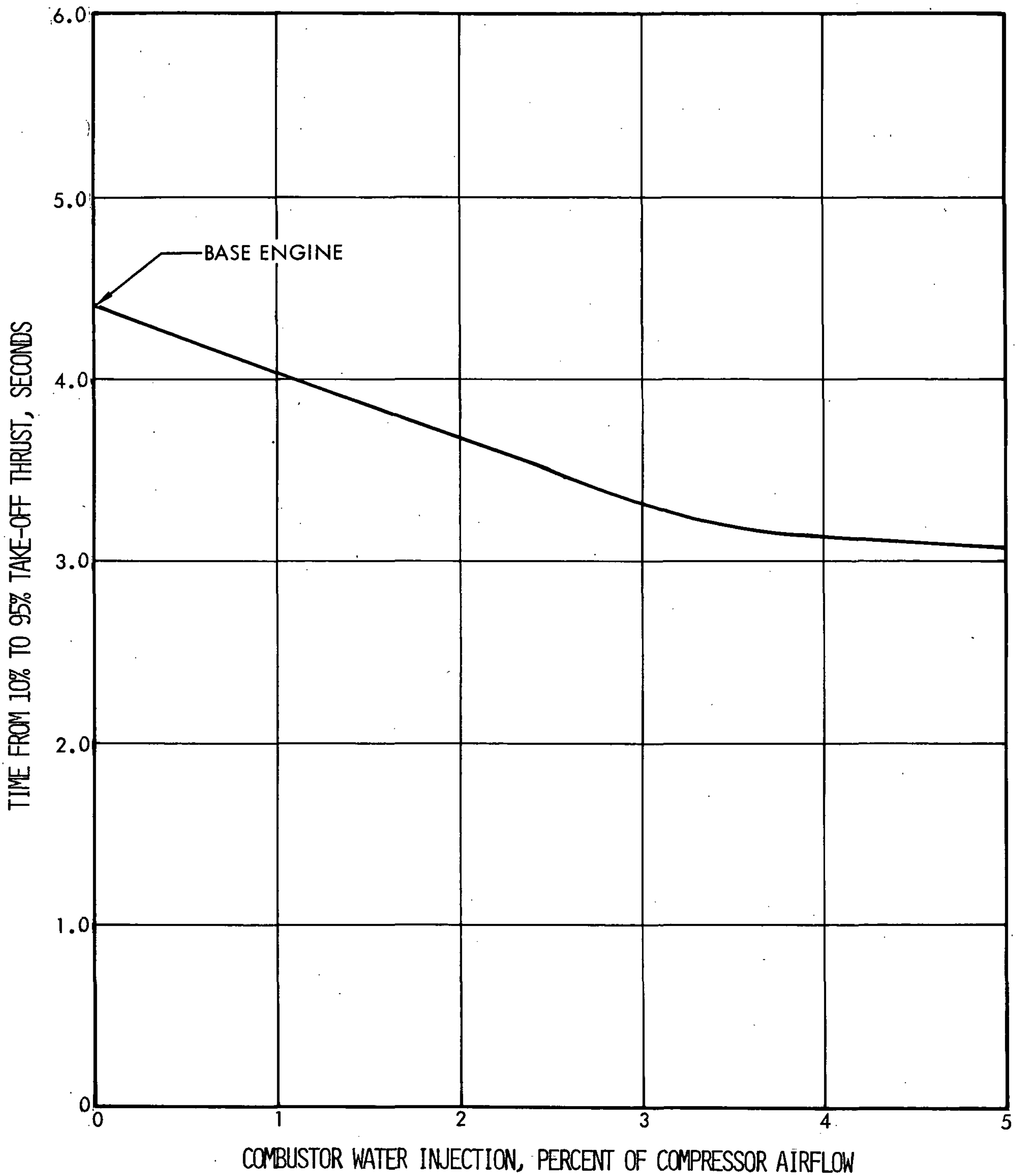



Figure 15. Effects of Water Injection on Thrust Response.

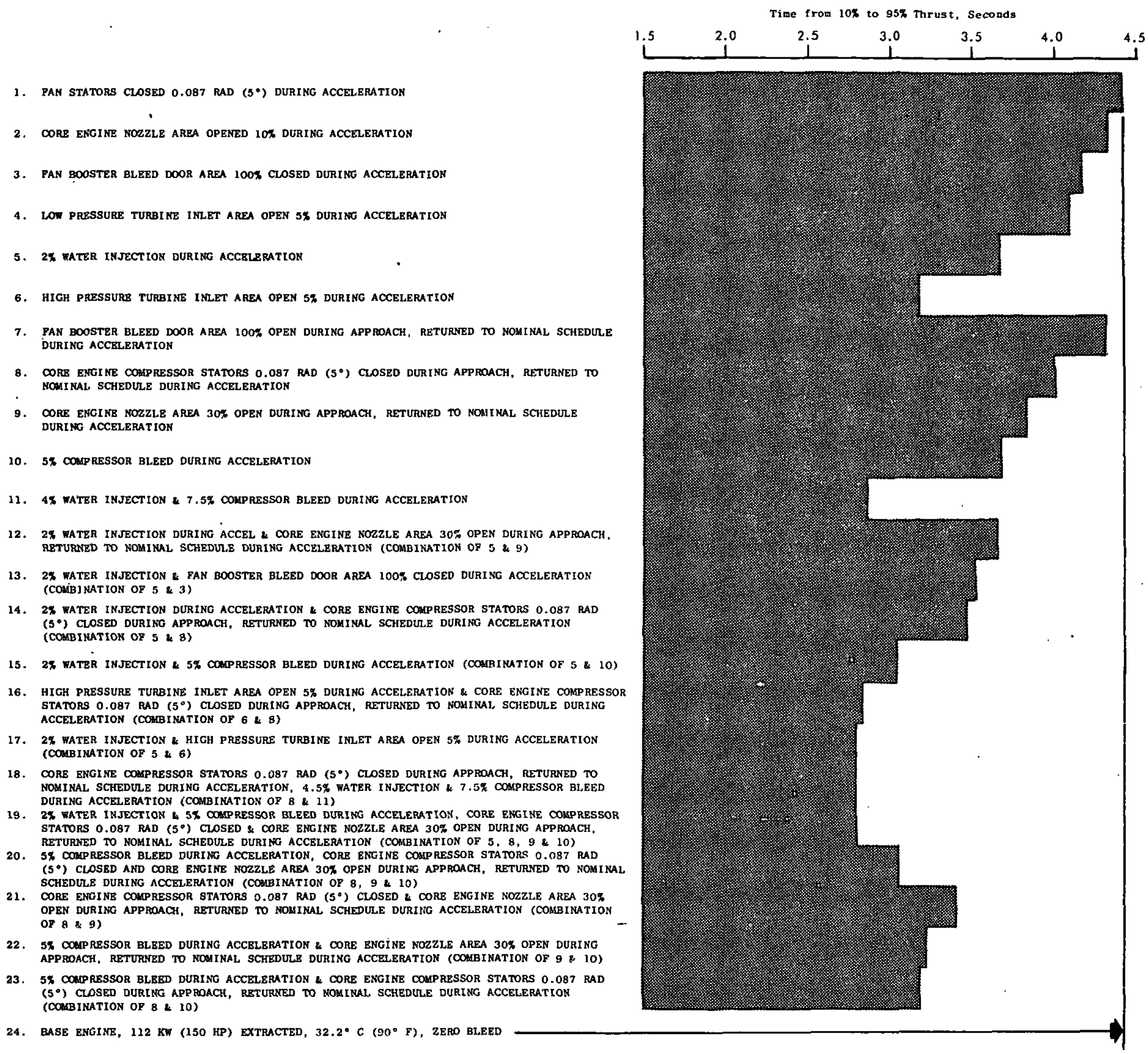



Figure 16. Response Time Results.

and for rapid acceleration; two or more variables were used for approach thrust attenuation only, for rapid attenuation and rapid acceleration.

Run 11 cannot be related directly to the basic runs although it can be compared to a combination of runs 5 and 10; however, the magnitude of the perturbation has been increased in run 11. Water injection into the combustor has been increased to 4% during acceleration (versus 2% water in run 5) and the continuous bleed has been increased to 7.5% (versus 5% in run 10); i.e., both approach attenuation and rapid acceleration were used. This run produced a 34.1% acceleration improvement. This run can be compared with run 15 which followed an identical procedure, but had only 2% water and 5% compressor bleed, producing a 30% improvement. Thus, the additional 2% water and 2.5% bleed produced a gain of 4.1% in transient performance.

Run 12 is a combination of runs 5 and 9. Prior to engine acceleration and during the higher angle glide slope of the approach, the exhaust nozzle area was opened 30% beyond nominal and the engine adjusted to provide 10% take-off thrust. The engine was then assumed to have reached steady-state conditions. At engine acceleration, the nozzle area was returned to its nominal scheduled area, and 2% water was injected into the engine combustor. Acceleration time was then 3.55 seconds or a 19.3% improvement.

Run 13 included 2% water injection and booster bleed door closure at the initiation time. This is a combination of runs 5 and 3, both rapid acceleration techniques. The thrust response improvement is compared to the base engine in Figure 16.

Run 14 is a combination of runs 5 and 8. Prior to engine acceleration and during aircraft approach on the higher angle glide slope, the core stators were closed 5° beyond the nominal schedule. At the initiation of engine acceleration, the core stators were returned to their nominal schedule and 2% water injection in the combustors was initiated. This combination resulted in a 21.6% improvement in acceleration time.

Run 15 provided a 30% improvement in acceleration time by combining runs 5 and 10 which consisted of 5% continuous compressor discharge bleed and 2% water injection during acceleration only.

Run 16 is a combination of approach thrust attenuation and rapid acceleration and is composed of runs 6 and 8. The core stators were closed 0.0872 radian (5°) beyond the nominal schedule for thrust attenuation. The high pressure turbine area was opened 5% beyond the nominal schedule, and the core stators were returned to the nominal schedule at the time the engine throttle was advanced to 100% thrust for rapid acceleration. This combination of thrust attenuation and rapid acceleration techniques reduced the acceleration time by 34.4%.

Run 17 is composed of two rapid acceleration techniques similar to runs 5 and 6. This includes 2% water injected into the combustors, and the high pressure turbine area ($A_{41}$) opened 5% greater than nominal during the engine

acceleration. This combination provided a 36.3% improvement which is the maximum improvement attained by any of the different schemes, although two other techniques did equally well. There were better acceleration rates, but they were at different base conditions. Figure 17 compares the response of run 17 to the base engine response.

Run 18 is a combination of three engine variables and serves to combine the effects produced in runs 8 and 11, which include both approach thrust attenuation and rapid acceleration techniques. Thrust attenuation was obtained by closing the core stators 0.0872 radian (5°) below the nominal schedule and bleeding 7.5% of core compressor discharge air overboard prior to engine acceleration while the aircraft is on the steepest leg of the two-segment glide slope. During engine acceleration, the 7.5% compressor bleed was continued, the core stators were returned to their nominal schedule, and 4% water was injected into the combustors. This procedure provided a 36.3% improvement in transient time which, along with two other procedures, provides the best results obtained during this study.

Run 19 utilized four engine variables in the process and includes both approach thrust attenuation and rapid acceleration techniques. This is the third combination which obtained a 36.3% reduction in acceleration time and is also the maximum reduction obtained during the evaluation. The four techniques employed were: 5% bleed, core stators closed 0.0872 radian (5°) beyond the nominal schedule, exhaust nozzle area opened 30% beyond nominal, and 2% (of core engine airflow) of water injection prior to acceleration during the initial glide slope. During the engine acceleration, both nozzle area and core stators were returned to their nominal schedule, 5% compressor bleed was sustained, and 2% water injection was initiated and sustained. This is a combination of the techniques used in runs 5, 8, 9, and 10.

Run 20 is similar to run 19 except that it does not include the water injection; otherwise, the remaining conditions are identical. Without water injection in run 19, the improvement in acceleration time is 30%. The water injection used in run 19 resulted in a 6.3% acceleration time improvement, compared to run 20 without water.

Run 21 combines two approach thrust attenuating techniques; i.e., runs 8 and 9. The core stators are closed 0.0872 radian (5°) from nominal and the nozzle area is opened 30% during the initial glide slope; both are returned to nominal at the initiation of acceleration. These two techniques produced an integrated improvement in acceleration time of 22.7%. If the engine requires a variable area nozzle for normal operation, recognizing that the engine will include variable core stators, this particular technique represents a minimal mechanical redesign and appears quite attractive from that aspect. Many of the other techniques provided better results, but will necessitate more mechanical changes and their associated weight and cost additions.

Run 22 is another combination of two variables utilizing thrust attenuation and rapid acceleration. It is composed of the effects of Runs 9 and 10, namely: 5% compressor bleed and nozzle area opened 30% beyond nominal prior to engine acceleration. The nozzle area is returned to its nominal schedule, and the 5%

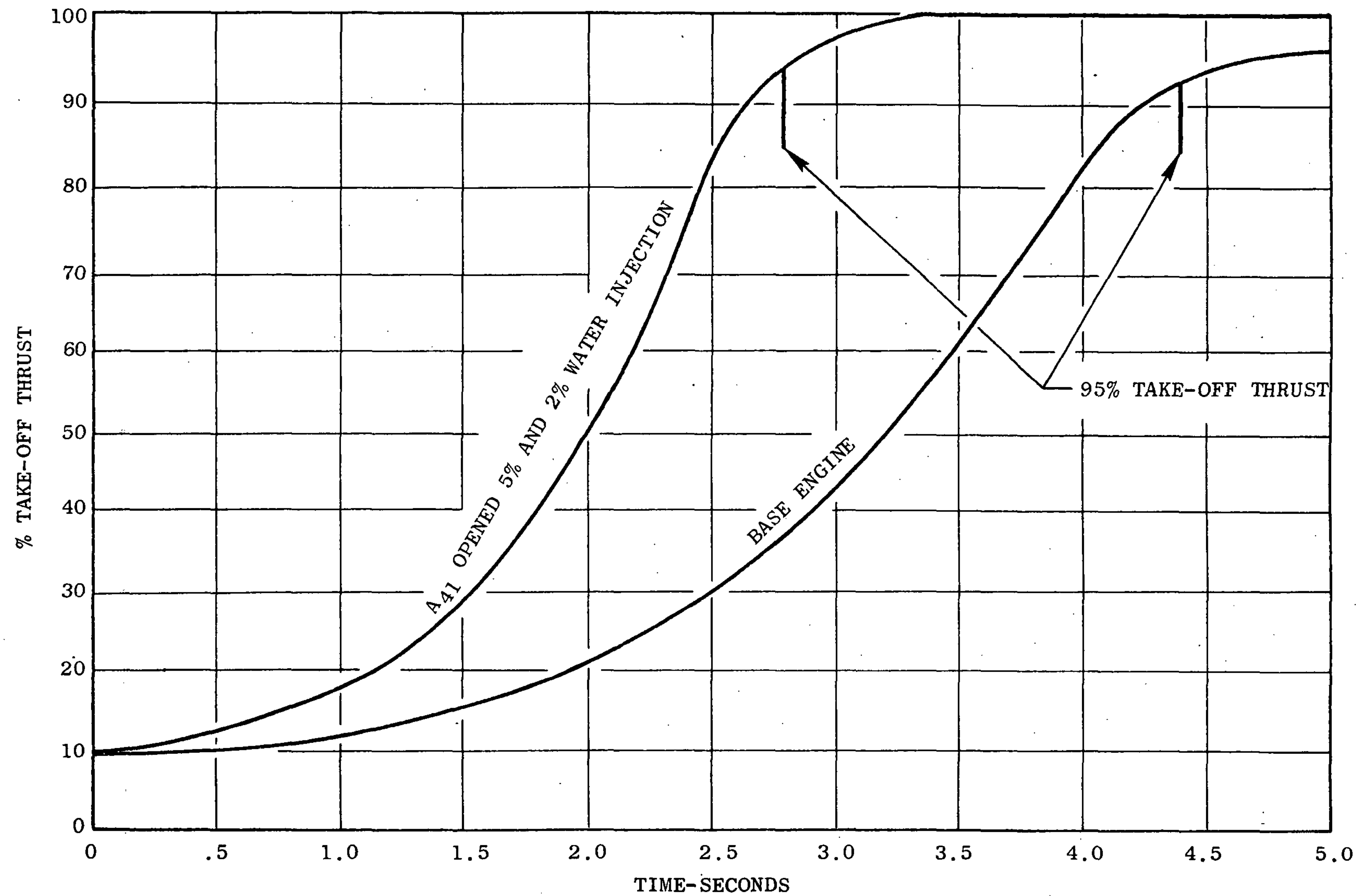



Figure 17. Thrust Response with Water Injection and HP Turbine Area.

bleed is continued during the engine acceleration. This combination improved the transient response by 25.9%. These two techniques will also require little modification to the present engine design to obtain this capability.

Run 23 is a combination of runs 8 and 10 and includes both approach thrust attenuation and rapid acceleration. The core stators were closed 0.0872 radian (5°) below nominal, and 5% compressor bleed was initiated during the initial glide slope for thrust spoiling. The stators were returned to their nominal schedule during the acceleration, and the 5% bleed was continued for rapid acceleration. This combination produced a 26.4% improvement in transient thrust response. This combination is also one of the more economical potential techniques for improving thrust response on an engine.

### Summary of Results

The different schemes investigated and summarized in Figure 16 improved the engine transient performance by varying degrees. The shortest acceleration time obtained was 2.8 seconds, a 36.4% improvement compared to 4.4 seconds for the base engine (as shown by runs 17, 18, and 19 in Figure 16). Thus, it is possible to improve engine transient response by operating on some of the various engine geometrics. Some of the schemes will be considerably more difficult to mechanize (methods used in Runs 4 and 6) than others. Those schemes which utilize core stators, compressor discharge bleed, and variable nozzle area will be easier to mechanize than many of the others since these variable geometry functions currently exist on many jet engines.

Although the base engine could have been redefined to obtain a shorter acceleration time, the General Electric approach to the study was to select those techniques which provided the most improvement in transient response from the existing base. Accordingly, the percent reduction in acceleration time (rather than an absolute level) served as the figure of merit to evaluate the various schemes that were investigated.

## CONCLUSIONS

- Several effective methods to improve engine response time from flight idle (10% take-off thrust) to take-off thrust have been identified using a representative dynamic engine model. Improvements up to 36.4% have been shown.

- Approaches which utilize features that are already on the engine such as variable stators, bleed air extraction, and variable exhaust nozzle should be given preference over those which require major engine changes such as variable turbine nozzles.

- Before any definite technique can be recommended, the impact on engine life, reliability, control complexity, engine performance, and the aero and mechanical problems must be assessed.

## RECOMMENDATIONS

It is not now known to what extent improvements in engine transient response will be required for the different approach procedures. It is recommended, therefore, that engine response requirements be established for representative aircraft by appropriate analysis and flight simulator experiments. Once these requirements are more firmly established, further engine studies based on these requirements should be conducted. This would include effects on life, complexity, and other engine characteristics for the specific techniques of greatest potential.

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## APPENDIX

## SYMBOLS

| | | |
|---|---|---|
| $A_8$ | - | Exhaust Nozzle Area |
| $A_{24}$ | - | Fan-Booster Bleed Door Area |
| $A_{41}$ | - | High Pressure Turbine Inlet Area |
| $A_{49}$ | - | Low Pressure Turbine Inlet Area |
| $A_{pp}$ | - | Approach |
| ATT | - | Advanced Transport Technology |
| $\beta_C$ | - | Core Stators |
| $\beta_F$ | - | Fan Inlet Guide Vanes (IGVs) |
| C | - | Closed |
| $H_2O$ | - | Water Injection in the Combustor |
| HP | - | High Pressure |
| HPE | - | Shaft Horsepower Extraction |
| IGV | - | Inlet Guide Vanes |
| LP | - | Low Pressure |
| Nom | - | Nominal |
| $N_1$ | - | Fan Rotor Speed - rpm or percent rpm |
| $N_2$ | - | Core Rotor Speed - rpm or percent rpm |
| O | - | Open |
| PCNHR | - | Percent Corrected Speed HP Rotor (% $N/\sqrt{\theta_{25}}$ |
| PNdB | - | Perceived Noise, dB |
| $P_{SB}$ | - | Core Compressor Discharge Bleed Pressure |
| $P_{S3}$ | - | Core Compressor Discharge Static Pressure |

$SM_{25}$ - Core Compressor Stall Margin

SS - Steady State

$T_2$ - Fan Inlet Temperature

$T_{25}$ - Core Compressor Inlet Temperature

$T_{41}$ - HP Turbine Inlet Temperature

$T_{4B}$ - Turbine Blade Temperature

$W_B$ - Compressor Discharge Bleed

$W_{25R}$ - Core Compressor Airflow

$\theta_{25}$ - Temperature Correction $\left[T_{25}(°\ R)/518.67 \text{ or } T_{25}(°\ K)/288.15\right]$

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